# Impacts of initial conditions on low-power transient in reload PWR cores

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## 1. Introduction

A time-dependent behaviour of a reload PWR cores at near hot zero power (HZP) subjected to an increase in the reactivity has been investigated by employing a point reactor model with a simplified heat balance model to accommodate the reactivity feedbacks. The presence of external neutron source, which originates from the spontaneous fission reactions in the burned fuels for such cores, enforces the reactor to be subcritical. The degree of such subcriticality depends on both the magnitude of external source and initial power, which are usually hardly known. This work is mainly concerned with the effects of variations in those parameters on the transient response of the reactor.

## 2. Models and Methods

*2.1* Point Kinetic Equation

A properly-weighted integration of the space- and time-dependent neutron diffusion equations can lead the following point kinetic equations:

$$\frac{dp}{dt} = \left[\frac{\rho(t) - \beta(t)}{\Lambda(t)}\right] p(t) + \frac{1}{\Lambda_0}\sum_k \lambda_k \xi_k(t) + \frac{s(t)}{\Lambda(t)}, \quad (1)$$

$$\frac{d\xi_k}{dt} = -\lambda_k \xi_k(t) + \frac{F_\lambda(t)}{F_{\lambda 0}}\beta_k(t)p(t), \quad (2)$$

where each parameter requires the knowledge for shape and adjoint flux [1, 2]. The ignorance of both information can be circumvented by assuming the shape to be the analytical solution of a homogeneous cylindrical core and approximating the adjoint flux to be unity in this preliminary study. Further simplifications are made by ignoring the time dependency of $\beta(t)$, $\Lambda(t)$, and the reduced external source *s(t)*:

$$\frac{dp}{dt} = \left[\frac{\rho(t) - \beta_0}{\Lambda_0}\right] p(t) + \frac{1}{\Lambda_0}\sum_k \lambda_k \xi_k(t) + \frac{s_0}{\Lambda_0}, \quad (3)$$

$$\frac{d\xi_k}{dt} = -\lambda_k \xi_k(t) + \beta_{k0} p(t). \quad (4)$$

For the initial steady state, one can yield the following relation based on Eqs. (3) and (4).

$$\rho_0 = -\frac{s_0}{p_0} \quad (5)$$

*2.2* Heat Balance Equation

Change in the power of the reactor will manifest in the variation of fuel, cladding, and coolant temperatures. Heat balance between such components can be written as the following equations [3].

$$M_f c_f \frac{dT_f}{dt} = p(t) - \frac{1}{R_g}[T_f(t) - T_{cl}(t)] \quad (6)$$

$$M_{cl} c_{cl} \frac{dT_{cl}}{dt} = \frac{1}{R_g}[T_f(t) - T_{cl}(t)] - \frac{1}{R_c}[T_{cl}(t) - T_c(t)] \quad (7)$$

$$M_c c_c \frac{dT_c}{dt} = \frac{1}{R_c}[T_{cl}(t) - T_c(t)] - 2wc_c[T_c(t) - T_i(t)] \quad (8)$$

Subscripts *f, cl,* and *c* represents fuel, cladding, and coolant, respectively. Notations *M, c,* $R_g$ , $R_c$ and *w* indicates the mass of the component, heat capacity, thermal resistance between fuel and clad, thermal resistance between clad and coolant, and mass flow rate, respectively.

*2.3* Feedback Effects

The reactivity feedbacks originating from moderator temperature, fuel temperature, and Xe-135 concentration are estimated in the following way:

$$\Delta\rho_m = -\frac{\partial\rho}{\partial T_m}\Delta T_m \approx MTC \times (T_m - T_{m0}), \quad (9)$$

$$\Delta\rho_f = -\frac{\partial\rho}{\partial T_f}\Delta T_f \approx FTC \times (T_f - T_{f0}), \quad (10)$$

$$\Delta\rho_{Xe} = \rho_{Xe,100} \times \left(\frac{Xe_{P_0}}{Xe_{100}}\right) \times \left(\frac{Xe(t) - Xe_{P_0}}{Xe_{P_0}}\right). \quad (11)$$

The concentration for Xe-135 was estimated for each time step via solving its balance equation, and subscript 100 indicates the concentration of such isotope at full power (2800 MWth) condition.

*2.4* Estimation of the external source contribution

Based on a fuel depletion calculation carried out with the ORIGEN-ARP 2.0 code, authors have estimated the spontaneous fission source contribution from once and twice burned fuel assemblies (FA) to be 20,000 [#/kgHM*sec] and 260,000 [#/kgHM*sec], respectively, for a typical reload PWR core. The core was assumed to consist of 28 fresh FAs, 64 once burned FAs, and 65 twice burned FAs. Such information can be lumped into the external source through Eq. (12):

$$s_0 = \frac{(\phi^*_{\lambda 0}, S_0)}{(\phi^*_{\lambda 0}, F_0\psi_0)} \approx \frac{(w, S_0)}{(w, F_0\,\psi_{approx})}, \quad (12)$$

where subscript *approx* indicates the approximate flux solution for 2-group homogeneous diffusion equation in a bare cylindrical reactor. A uniform weighting vector *w*

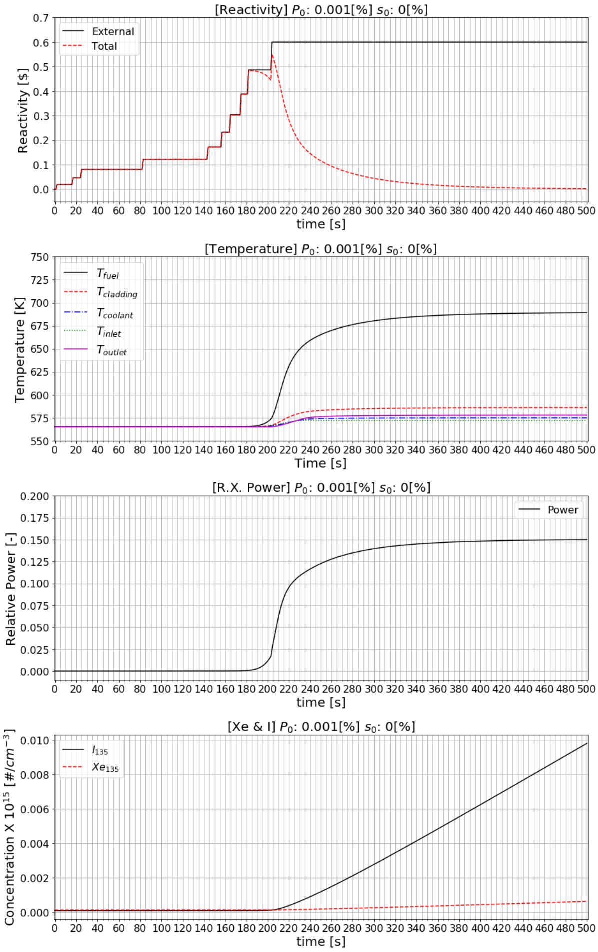


Fig. 1. Evolution of physical variables for initial power of 0.001 % without considering the external source effect

was introduced for each group to encompass the energy dependency of external source, which its magnitude being proportional to the integration of *approximate* adjoint flux.

Neutron generation time can be deduced from Eq. (13):

$$\Lambda_0 = \frac{\left(\phi^*_{\lambda 0}, \frac{\psi_0}{v_0}\right)}{\left(\phi^*_{\lambda 0}, F_0\psi_0\right)} \approx \frac{\left(w, \frac{\psi_{approx}}{v_0}\right)}{\left(w, F_0\, \psi_{approx}\right)}, \qquad (13)$$

where $v_0$ indicates the representative neutron velocity for each group. Table 1 summarizes the physical quantities used in the numerical simulation.

## 3. Numerical Results

Aforementioned reactor system was subjected to an increase in the external reactivity by +0.6$ in a step-wise manner. After the ramp-up, the reactivity was either retained or decreased. Figure 1 depicts the evolution of net reactivity considered in this work, temperature, power, and Xe-135 concentration for an initial power of 0.001 %, without any external source for a prescribed inlet temperature. One can note that, due to the feedback effects, both temperature and power show saturating behaviour along with the decrease in the net reactivity.

| Point Kinetic Equation | | |
|---|---|---|
| $\Lambda_0$ | $1.91 \times 10^{-5}$ | [sec] |
| $s_0$ | 1820.91 | [#/sec] |
| $v_{0,thermal}$ | 220,000 | [cm/sec] |
| $v_{0,fast}$ | $\infty$ | [cm/sec] |
| $\nu\Sigma_{f,thermal}$ | 0.18514 | [1/cm] |
| $\nu\Sigma_{f,fast}$ | 0.008476 | [1/cm] |

| Heat Balance Equation | | |
|---|---|---|
| $M_f$ | 65,722 | [kg] |
| $M_{cl}$ | 13,539 | [kg] |
| $M_c$ | 151,456 | [kg] |
| $R_g$ | $2.4546 \times 10^{-7}$ | [K/W] |
| $R_c$ | $2.6659 \times 10^{-8}$ | [K/W] |
| $w$ | 10,516 | [kg/sec] |

| Feedback Coefficients | | |
|---|---|---|
| MTC | $-3.0 \times 10^{-5}$ | [1/K] |
| FTC | $-1.0 \times 10^{-5}$ | [1/K] |
| $\rho_{Xe,100}$ | $-2800 \times 10^{-5}$ | [-] |

Table I: Physical Quantities used for Simulation

Two different scenarios have been tested, one retains the insertion of +0.6$ reactivity after ramp-up (CASE 1), and the other case (CASE2) imposes a step-wise ramp-down of the external reactivity after reaching apex of +0.6$.

### *3.1* (CASE1) Response for retainment of reactivity

Figure 2 illustrates the evolution of reactivity and power subjected to an increase in the external reactivity while varying the initial power and external source contribution. For the case of not having external source, as initial power dwindles, additional time is required for the full development of the reactor power, which accords with the slower decrease in reactivity after reaching its maximum. The plateaus for such cases were identical in its magnitude.

On the other hand, the presence of external source manifests in seemingly no disparity for reactivity and reactor power, regardless of the initial condition. Such phenomenon can be understood as external source being the dominant term for varying the power evolution.

### *3.2* (CASE2) Response for dwindling the reactivity

Figure 3 shows the response of the system subjected to a ramp-up and ramp-down of the external reactivity. Without consideration of external source, as initial power decreases, the maximum power exhibits decreasing tendency. Such phenomenon can be understood by an insertion of negative reactivity before the full development of power as shown in Figure 2.

Taking external source into account, regardless of the initial condition, the evolution of power and reactivity is identical for each case.

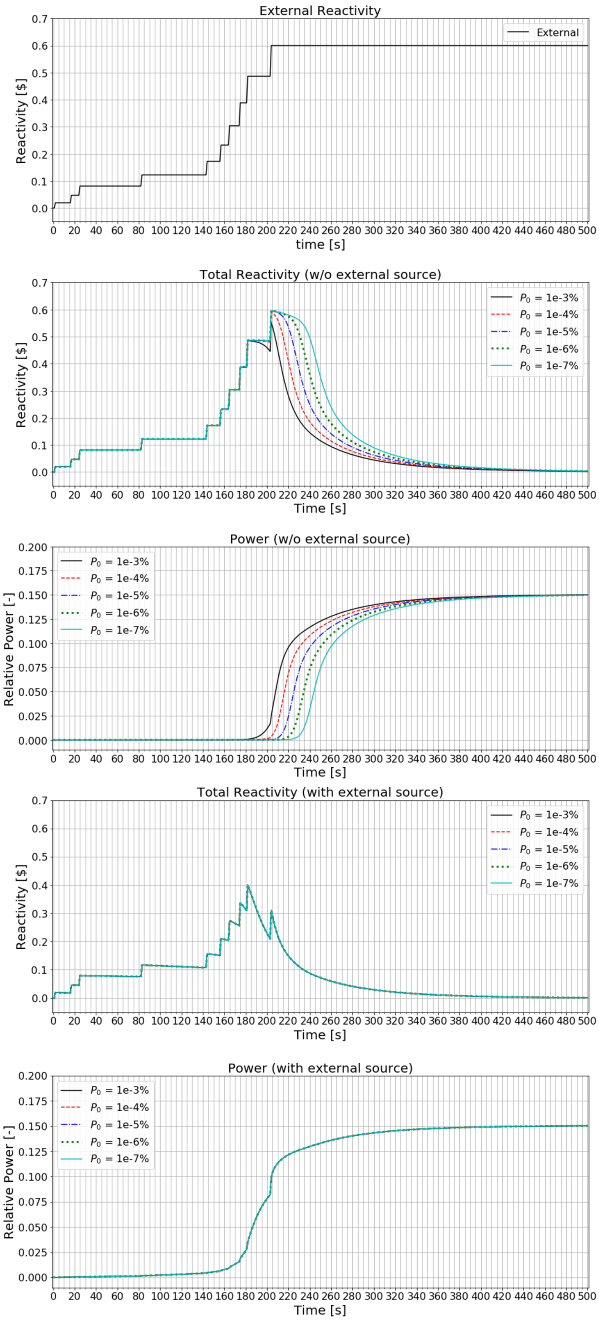


Fig. 2. *(CASE1)* Evolution of reactivity and power for varying initial power for ramp-up of external reactivity.

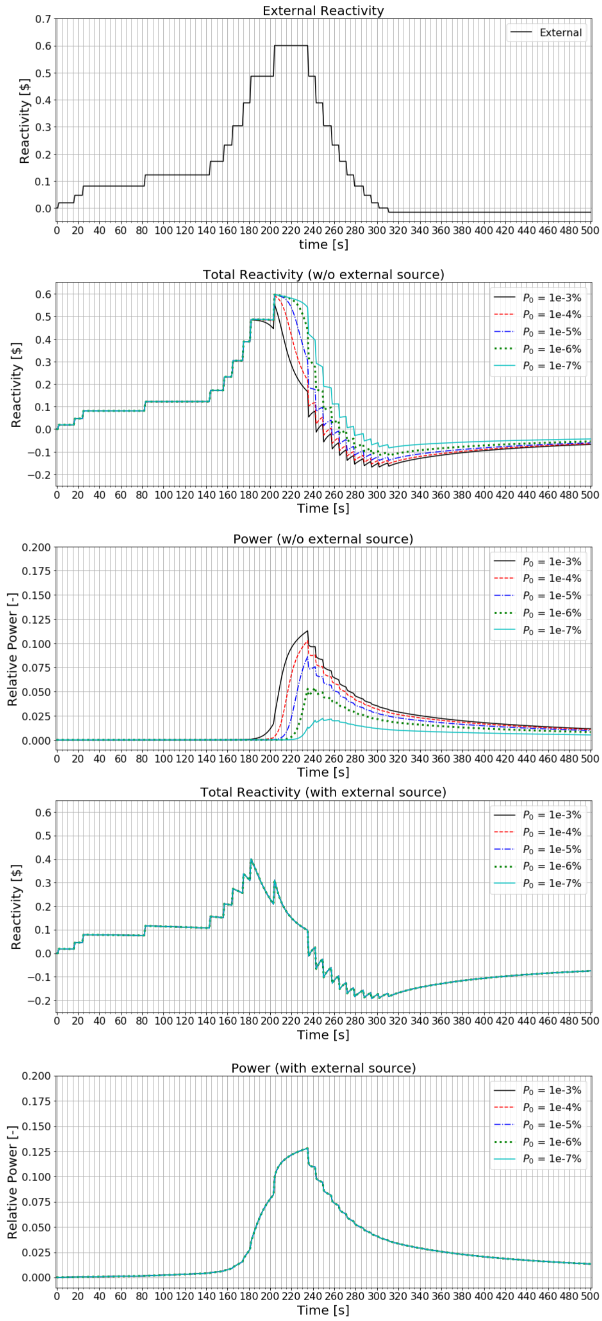


Fig. 3. *(CASE2)* Evolution of reactivity and power for varying initial power for ramp-up and ramp-down of external reactivity.

*3.3* Variation of magnitude of external source

The response of the reactor while adjusting the magnitude of the external source for each case are given in Figure 4. As the magnitude increases, less time is required to observe the ascension in power. However, the saturation level shows no significant deviation for the *(CASE1)* scenario.

*3.4* Substantial decrease in the initial power

Although the results presented in *3.2* do not exhibit disparity in both reactor power and reactivity for variation in the initial power, one can anticipate that deviation may occur when the magnitude of inherent negative reactivity becomes significant enough. From Eq. (5), the variation of such quantity can be deduced as a function of initial power, which is shown in Figure 5 along with the simulation result.

Without the consideration of external source, only the time required for the development of power increases. Considering the external source effect, unless the initial power was smaller than $10^{-11}$ %, there were no variation in the plateau of power; however, due to an internal reactivity of about -0.05$ for $10^{-11}$ % case, noticeable decrease in the plateau was observed for such condition.

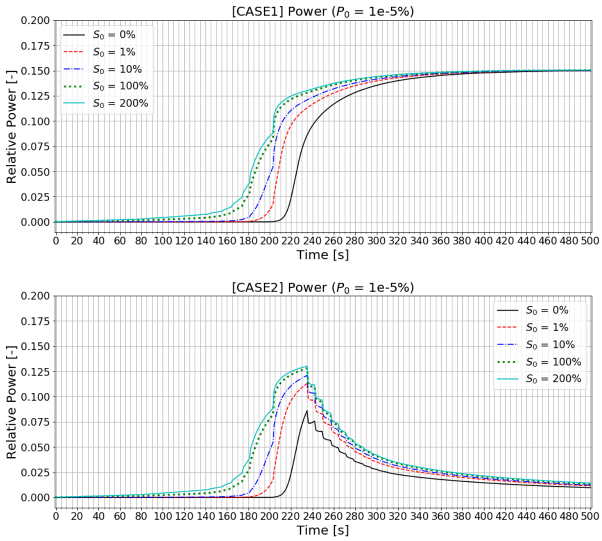


Fig. 4. Effect of variation in the magnitude of external source for fixed initial power.

### *3.5* Variation in the magnitude of external reactivity

Figure 6 depicts the time evolution of reactor power subjected to different magnitudes of external reactivity. Provided reactivity was altered to have either 5% increment or decrement in its magnitude. The plateau of power for (*CASE 1*) scenario increased with an additional external reactivity, although the saturation level did not vary regardless of the presence of external source when the external reactivity was fixed to a certain value.

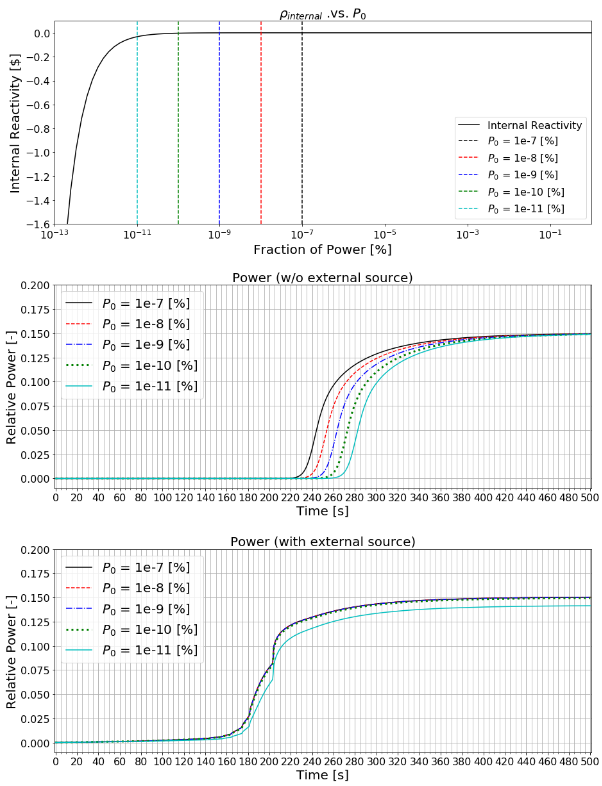


Fig. 5. Calculated internal negative reactivity as a function of initial power along with the (CASE1) simulation result.

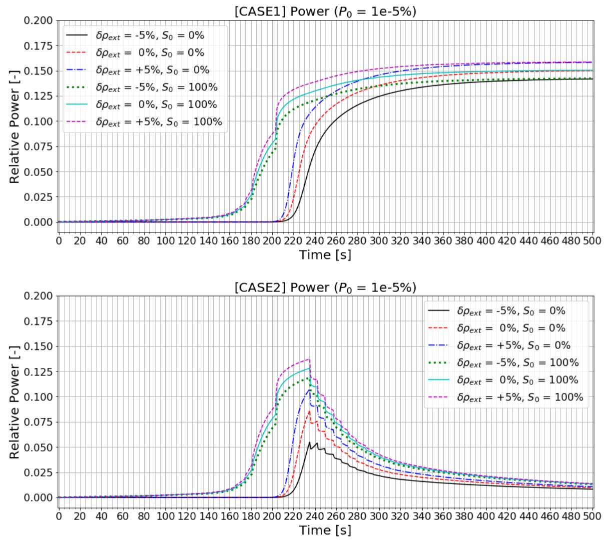


Fig. 6. Response of power for varying external reactivity.

Discrepancy in the maximum power was observed for (*CASE 2*) scenario where descent of net reactivity occurred before the full development of reactor power. The initial power was fixed to be $10^{-5}$ % for all the cases.

## 4. Conclusions

The impacts of variation in the initial conditions regarding the response of a reload PWR reactor subjected to variation in the external reactivity have been investigated. The authors have found that the presence of external source results in a negative internal reactivity, which decreases the magnitude of net reactivity response. However, the presence of external source compensates the decrease in the net reactivity, resulting in an unchanged saturation level unless the initial power becomes smaller than a certain value.

For the case of decreasing the reactivity after reaching its peak value, i.e., ramp-down, the deviation in the response time for the development of power results in a significant variation for maximum power when external source is neglected. Such disparity is strongly suppressed when the external source is considered.

In conclusion, the presented work undeniably implies that external source must not be neglected while estimating the transient response of the reload PWR reactor system near hot zero power.

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